

# Improvement of the thermal and mechanical flow characteristics in the exhaust system of piston engine through the use of ejection effect

L V Plotnikov<sup>1</sup>, B P Zhilkin<sup>1</sup>, Yu M Brodov<sup>1</sup>

<sup>1</sup>Ural Federal University named after the first President of Russia B.N. Yeltsin, ul. Mira 19, Ekaterinburg 620002, Russia

E-mail: plotnikovlv@mail.ru

**Abstract.** The results of experimental research of gas dynamics and heat transfer in the exhaust process in piston internal combustion engines are presented. Studies were conducted on full-scale models of piston engine in the conditions of unsteady gas-dynamic (pulsating flows). Dependences of the instantaneous flow speed and the local heat transfer coefficient from the crankshaft rotation angle in the exhaust pipe are presented in the article. Also, the flow characteristics of the exhaust gases through the exhaust systems of various configurations are analyzed. It is shown that installation of the ejector in the exhaust system lead to a stabilization of the flow and allows to improve cleaning of the cylinder from exhaust gases and to optimize the thermal state of the exhaust pipes. Experimental studies were complemented by numerical simulation of the working process of the DM-21 diesel engine (production of "Ural diesel-motor plant"). The object of modeling was the eight-cylinder diesel with turbocharger. The simulation was performed taking into account the processes nonstationarity in the intake and exhaust pipes for the various configurations of exhaust systems (with and without ejector). Numerical simulation of the working process of diesel was performed in ACTUS software (ABB Turbo Systems). The simulation results confirmed the stabilization of the flow due to the use of the ejection effect in the exhaust system of a diesel engine. The use of ejection in the exhaust system of the DM-21 diesel leads to improvement of cleaning cylinders up to 10 %, reduces the specific fuel consumption on average by 1 %.

## 1. Introduction

Improvement of technical and economic indicators of piston internal combustion engines (ICE) is achieved by improving the fuel and turbocharger systems, as well as gas exchange, mixture formation and combustion processes [1-4]. There is a considerable reserve for increasing the efficiency of the piston engines by improving thermal and mechanical characteristics of flows in the exhaust system. A number of requirements to exhaust systems of internal combustion engines is presented [5-8]. The main requirement is the most complete cleaning of the cylinders from the exhaust gases. It is known that the quality of cleaning of the cylinder is mainly determined by the geometric configuration of the exhaust systems and the nature of gas flow. Stagnant zones and reverse pressure waves are negative phenomena, which are typical for exhaust systems of piston ICEs [1, 5]. The creation of the ejection effect in the exhaust system is one of the ways to reduce the effect of these phenomena; some of their design are described in [9]. Однако Similar exhaust systems are based on the harmonization of gas-dynamic events

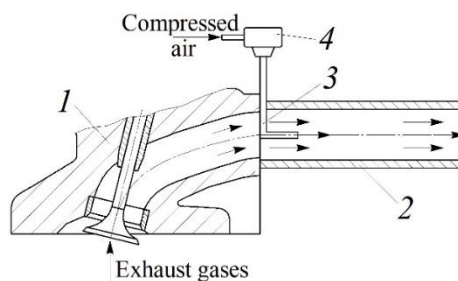


from the work of various cylinders. They are quite complex and can only be used on large-size diesel engines.

The original way of modernization of the exhaust systems of piston engines due to the application of the ejection effect is proposed on the basis of the results of physical and numerical simulation. This method allows to stabilize the flow of gases and to improve technical and economic performance of piston engines.

## 2. The design of the exhaust system with ejector tube

The method of improving the exhaust system based on the creation of the ejection effect was proposed on the basis of analysis of literature and pilot studies. The basic idea of ejection is to create additional rarefaction in the exhaust pipe, which will contribute to a better cleaning of the cylinder from exhaust gases. In this case, the technical solution was as follows: ejector tube was mounted in the exhaust pipe, air was supplied into the tube through the electro-pneumatic valve. [10]. Thus, the additional rarefaction is created in the exhaust system, which stabilize the flow of gases and reduce the transients in the boundary layer. The design of the proposed method is shown on Figure 1.



**Figure 1.** Scheme of exhaust system of a piston engine with forced ejection [10]: 1 – engine cylinder head; 2 – exhaust pipe; 3 – ejector tube; 4 – electro-pneumatic valve.

Sketches of exhaust systems with forced ejection for various engines were performed. It was found that such exhaust systems can be implemented without major structural changes and financial costs for most modifications of piston ICEs.

## 3. Experimental setups and measurement equipments

Experimental setup for experimental studies of gas dynamics and heat transfer in exhaust systems of piston engines has been developed. It was a full-scale model of a single-cylinder engine of dimension 8.2/7.1. The experiments were carried out for a traditional exhaust system and exhaust system with ejector tube. The range of the crankshaft rotation  $n$  was from 600 to 3000 rpm. Excess pressure in the exhaust process  $p_b$  (the pressure in the cylinder before the exhaust valve) was from 0.5 to 2.0 bar. The average air temperature in the exhaust system was 40 °C. Compressed air into the ejector tube came from an autonomous compressor in the exhaust system with forced ejection. Rarefaction (static pressure) in the exhaust pipe behind the ejector tube was 0.05 bar.

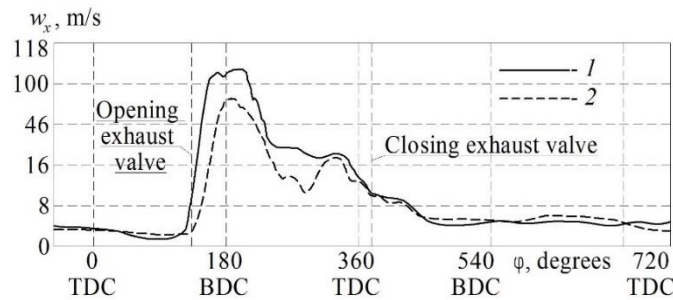
The constant temperature anemometers were used to determine the velocity ( $w_x$ ) of the gas flow and the local heat transfer coefficient ( $\alpha_x$ ). Measurements of the engine crankshaft speed were carried out using tachometer. All experimental data were entered into an automated measuring system based on analog-to-digital converter.

A more detailed description of the experimental setup and measurement tools are presented in the monograph [11].

## 4. The main results of experimental studies

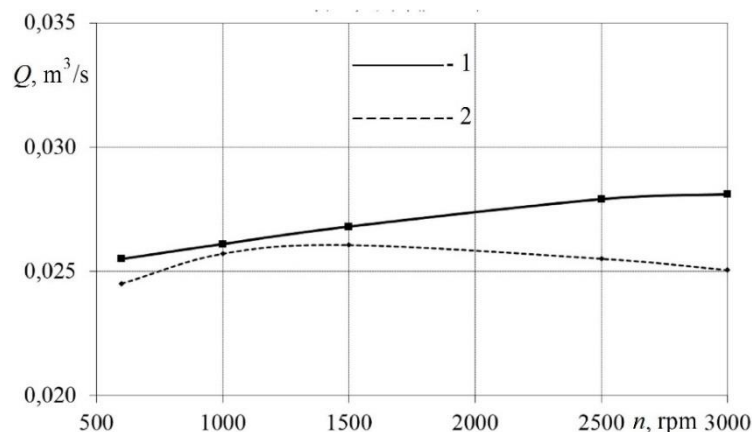
Comparison of gas-dynamic and flow characteristics of gas flows in the exhaust system with the forced ejection and without it is shown in Figures 2 and 3.

It is established that the maximum value of the flow velocity  $w_x$  in the exhaust system with a forced ejection is much higher (up to 35%) than in the system without it (Figure 2). It should be noted that the smoothing of fluctuations of velocity and pressure of the gas flow in the exhaust system with the ejection occurs in the opening period of the exhaust valve. This indicates a stabilization of the flow, which is a consequence of creating additional vacuum in the exhaust system due to the forced ejection.



**Figure 2.** The dependence of the local ( $l_x = 140$  mm,  $d = 30$  mm) velocity  $w_x$  of the gas flow in the exhaust system with ejection (1) and traditional system (2) from the crankshaft angle when the rotational speed of a crankshaft  $n = 1500$  rpm and at an initial pressure of  $p_b = 2,0$  bar.

The change in gas dynamic characteristics of gas flow affects the gas flow rate through the exhaust system with ejector tube (Figure 3).

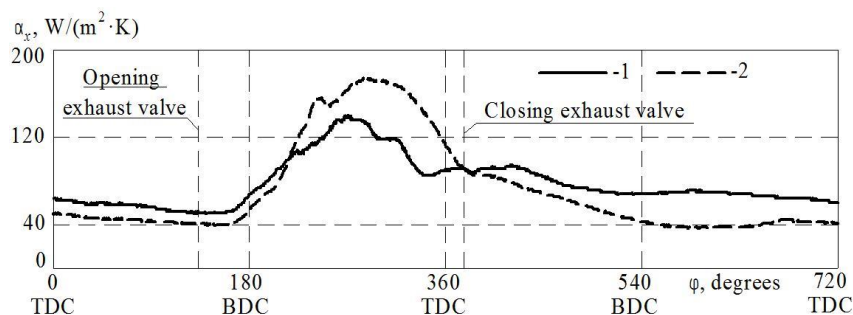


**Figure 3.** The dependence of volumetric air flow  $Q$  through the exhaust system with ejection (1) and traditional system (2) from the crankshaft rotation frequency.

The volumetric flow rate  $Q$  through the exhaust system with forced ejection increases in the whole investigated range of the crankshaft rotation frequency  $n$  (Figure 3). It should be noted that an increase of the the volumetric gas flow through the exhaust system with ejection is 1.5 to 3.9% at a crankshaft rotation speed of up to 1500 rpm, and the growth of  $Q$  is almost 10 % for  $n = 3000$  rpm. This should lead to better cleaning of the cylinders from exhaust gases and, accordingly, to increase engine power.

The impact of forced ejection on the local heat transfer coefficient from the exhaust gases to the walls of the pipe is shown on Figure 4.

The maximum values of the local heat transfer coefficient  $\alpha_x$  are reduced on average by 20 % with the installation of ejection tube in the exhaust system (Figure 4). It should be noted that the intensity of heat transfer is somewhat higher in the exhaust system with ejection during the closed exhaust valve. It should also be noted that the smoothing of fluctuations of velocity and pressure flow occurs in the exhaust system with ejection during the period of open exhaust valve.



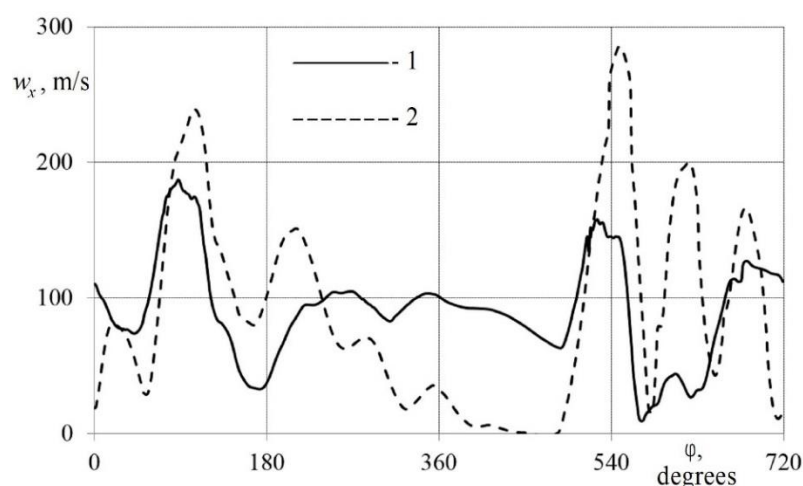
**Figure 4.** The dependence of the local ( $l_x = 140$  mm,  $d = 30$  mm) heat transfer coefficient  $\alpha_x$  in the exhaust system with ejection (1) and traditional system (2) from the crankshaft angle when the rotational speed of a crankshaft  $n = 3000$  rpm and at an initial pressure of  $p_b = 2,0$  bar.

Thus, we can assume that the use of the effect of ejection will reduce the thermal tensions of the exhaust system and increase its reliability, because there is a slight decrease in the intensity of heat transfer, and ejection air cools the exhaust gases additionally [12].

### 5. The main results of the numerical simulation

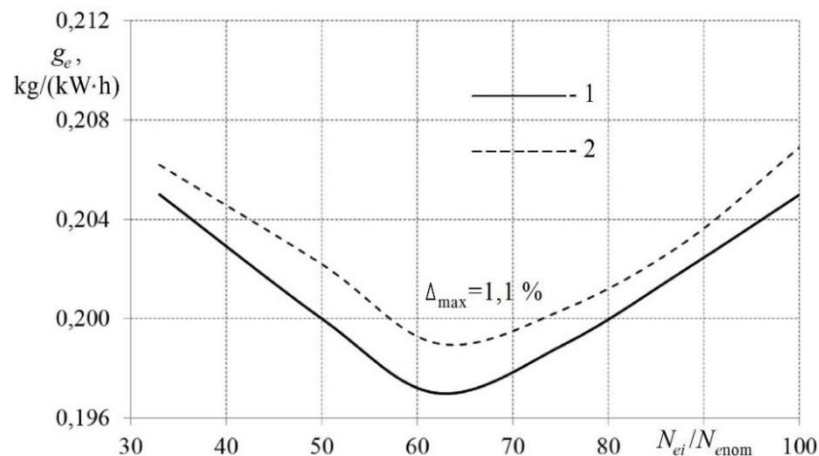
Numerical simulation of working process of diesel engine 8DM-21 (manufactured by «Ural diesel-motor plant», Ekaterinburg) in the software ACTUS (Switzerland, ABB Turbo Systems Ltd.) was carried out in this work. The software ACTUS allows to set the geometric characteristics of the intake and exhaust systems, the parameters of the turbocharger and also other essential indicators of the cylinder-piston group. Several scientific and technical articles based on modeling in ACTUS were presented at the world congress ASME and CIMAC [13, 14].

Numerical simulation confirms the results of experimental studies: smoothing of velocity and pressure flow pulsations occurs in the exhaust pipe. In particular, it is seen that the amplitude of pulsations of the flow velocity are reduced up to 50% in the exhaust system of the diesel engine 8DM-21 while maintaining average flow rate of gases (Figure 5).



**Figure 5.** The calculated dependences of the local flow velocity  $w_x$  in the exhaust system with ejection (1) and traditional system (2) when the rotational speed of a crankshaft  $n = 1500$  rpm and a power of 930 kW (for diesel engine 8DM-21).

The results of numerical simulation indicate that the coefficient of residual gases is reduced up to 10 % at the partial operation of the engine due to the use of forced ejection in the exhaust system of piston ICE. This leads to a decrease in the specific effective fuel consumption by an average of 1 % (Figure 6).



**Figure 6.** The calculated dependences of the effective specific fuel consumption  $g_e$  from the relative engine power  $N_{ei}/N_{enom}$  with different configurations of the exhaust system of the diesel engine 8DM-21: 1 – with ejection; 2 – without ejection.

It should be noted that the reduction in specific fuel consumption on average by 1 % for engine 8DM-21 will reduce the total fuel consumption to end consumers to approximately 2 kg/h. Thus, the total annual fuel costs will be reduced by about 8,000 euros in the process of operation.

## 6. Conclusions

The following main conclusions can be drawn on the results of the study of gas dynamics and heat transfer in exhaust systems of different configurations (with and without ejection):

- the main regularities of change of the instantaneous velocity and local heat transfer coefficient in the exhaust systems of different configurations (with and without ejection) for different modes of operation of the piston engine were determined;
- it is established that the decrease in the intensity of local heat transfer by up to 20% is due to the use in the exhaust system effect the ejection (this will allow to optimize the thermal state of the exhaust pipes);
- it is shown that the use of forced ejection in the exhaust system of piston ICE leads to an increase in gas flow rate through the system for 1.5-10 % depending on the operating mode of the engine; this will improve the scavenging of cylinders from the exhaust gas and improve technical and economic performance of piston engines;
- on the basis of numerical modeling in the software ACTUS it is shown that the use of forced ejection in the exhaust system of a diesel engine 8DM-21 leads to a decrease in the effective specific fuel consumption by up to 2.0 %.

## Acknowledgments

The work has been supported by the Russian Foundation for Basic Research (grant No. 16-38-00004).

## References

- [1] Dieghan T, Brown J, Dalby J, Valenta L, Kuchar P 2016 *CIMAC World Congress on Combustion Engine 28th* (Helsinki) p 169-181
- [2] Yang T, He S, Long W, Fu Y, Tian H, Feng L 2016 *CIMAC World Congress on Combustion*

- Engine 28th* (Helsinki) p 300-308
- [3] Ivashhenko N A, Neuburg L R, Kavtaradze R Z, Aliev I N 2016 *Herald of Bauman MSTU. (Ser MechEngineering* Vol 106) **1** 68-79
  - [4] Grishin Ju A, Kopylov A S 2015 *Proceedings of HEI (Ser Machine Building* Vol 667) **10** 31-37
  - [5] Draganov B H, Kruglov M G and Obuhova V S 1987 *The design of the intake and exhaust ducts of internal combustion engines* (Kiev: Vishcha shkola publ.) p 175
  - [6] Kavtaradze R Z 2008 *The theory of piston engines. A special Chapter* (Moscow: Bauman Press) p 720
  - [7] Heywood J B 1988 *Internal combustion engine fundamentals* (New York: McGraw-Hill) p 458
  - [8] Matsumoto I, Ohara A 1986 *SAE Techn. Pap. Ser.* (№ 860100) 1-11
  - [9] Efimov S I, Ivashhenko N A, Il'in V I, Alekseev V P 1985 *The internal combustion engines. Systems of piston and combined engines* (Moscow: Mashinostroenie) p 456
  - [10] Zhilkin B P, Plotnikov L V, Grigor'ev N I 2013 *Patent F02B 27/04* № 135728 RU
  - [11] Zhilkin B P, Lashmanov V V, Plotnikov L V and Shestakov D S 2015 *Process Improvement in gas-air path of piston internal combustion engines* (Ekaterinburg: Ural Press) p 228
  - [12] Brodov Y M, Grigoryev N I, Zhilkin B P, Plotnikov L V, Shestakov D S 2015 *Thermal Engineering* (Vol 62) **14** 1038-1042.
  - [13] Bernasconi S 2015 *ASME ICED Fall Division* (Huston) p 138-147
  - [14] Schurmann P 2013 *CIMAC Congress 2013* (Shanghai) p 677-685